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African Journal of Agricultural Research

Full Length Research Paper

Trace gas fluxes from intensively managed rice and soybean fields across three growing seasons in the Brazilian Amazon

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The emission of gases that may potentially intensify the greenhouse effect has received special attention due to their ability to raise global temperatures and possibly modify conditions for life on earth. The objectives of this study were the quantification of trace gas flux (N_2O, CO_2 and CH_4) in soils of the lower Amazon basin that are planted with rice and soybean, and the relation of this flux to soil physical and chemical parameters and to precipitation. This study was conducted in agricultural fields planted with rice (*Oryza sativa*) and soybean (*Glycine max*), located near the cities of Belterra and Santarém in western Pará State, Brazil, during the production years of 2005 to 2007. Measurements were done using static chambers in the field, and samples were analyzed by gas chromatography in the laboratory. Statistical analysis was conducted to determine variation in gas flux in both crops, and the results show that CO_2 flux varied between 305 and 227 mg-C $m^{-2}\,h^{-1}$ under rice, and 243 and 156 mg-C $m^{-2}\,h^{-1}$ under soybean. Flux of N_2O under rice varied between 4.5 and 20.4 µg-N $m^{-2}\,h^{-1}$, and under soybean flux variation was between 4.0 and 9.4 µg-N $m^{-2}\,h^{-1}$. Variation in flux of CH_4 under rice was between 5.1 and 14.0 µg-C $m^{-2}\,h^{-1}$, and under soybean it was 0.4 and 1.2 µg-C $m^{-2}\,h^{-1}$. These results demonstrate that, during the study period, the rice crop had higher flux for all trace gases than the soybean crop.

Key words: Amazon region, trace gas, crops.

INTRODUCTION

Land use change, the anthropogenic clearing of forest for agriculture, and agricultural practices are three of the main contributors to the increase in atmospheric greenhouse gas (GHG) concentrations (Houghton, 1991; Fearnside, 2005; IPCC, 2007) and, thus; climate changes. The main gases that contribute to the

greenhouse effect (GHG) are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and water vapor (H_2O) (Ostermayer, 2004). Without these gases, which act as a natural blanket around the earth, thermal infrared radiation absorbed by the earth´s surface would dissipate into space and the temperature of the planet would be approximately 20°C colder than the current global average of 15°C (Houghton, 2004). However, increased concentrations of GHG lead to retention of heat in the atmosphere, provoking disequilibrium in terrestrial ecosystems due to the increase in temperature. According to estimates of the Intergovernmental Panel on Climate Change (IPCC), the average global temperature will increase by 1.8ºC by the end of this century (IPCC, 2007). The consequences of this increase are affecting the quality of life currently experienced around the world and also for long-term agricultural sustainability.

The increase in the concentration of these gases in the atmosphere is principally due to anthropogenic actions manifested directly through fossil fuel burning, industrial production, and fires, and indirectly through the irrational use of natural resources (Cardoso et al., 2001).

Combined CO_2, CH_4, and N_2O contribute to more than 90% of anthropogenic climate warming gasses (Hansen et al., 2000). The fluxes of CO_2, CH_4, and N_2O are influenced by multiple factors, such as climate, nitrogen deposition, and land management practices. Agriculture releases to the atmosphere significant amounts of CO_2, CH_4, and N_2O (Smith et al., 2007; Metay et al., 2007). As a proportion of global anthropogenic emissions in 2005, agriculture contributed approximately 20% of CO_2 (Smith et al., 2007; Johnson et al., 2007) 58% of N_2O (Smith et al., 2007; Syakila and Kroeze, 2011), and 47% of CH_4, (Smith et al., 2007). Agricultural emissions of CH_4 and N_2O have increased globally by nearly 17% from 1990 to 2005 (IPCC, 2007), and agricultural N_2O emissions are projected to increase by 35 to 60% by 2030 due to increased nitrogen fertilizer use and increased animal manure production (FAO, 2003). Assuming that CH_4 emissions will grow in direct proportion to increases in livestock numbers, then global emissions from livestock is expected to increase by 60% by 2030 (FAO, 2003).

Land use change releases greenhouse gases when the forest is burned to clear the land (Houghton, 1991; Crutzen and Andreae, 1990; Goreau and Mello, 1988). Deforestation rates in the tropics have reached 2% of the total area, annually (Williams, 1990; Meyers, 1991). These deforested areas in the tropics are converted principally to plantations and pastures (Hecht, 1992; Fearnside, 2005). After land use change, agricultural practices such as soil tillage and application of mineral fertilizer affect soil gas emissions. Soil tillage accelerates decomposition of soil organic matter (SOM), whereas application of nitrogen-based fertilizer to the soil increases emissions of N_2O and NO (Davidson et al., 1996; Matson et al., 1996; Veldkamp et al., 1998; Crill et al., 2000; Mosier, 2001; Yan et al., 2001; Steudler et al.,

2002).

Due to recent agricultural expansion in the Amazon evaluation of impacts by this land use on greenhouse, gas emissions have become a research priority. Many studies have documented the emissions from pastures (Verchot et al., 1999; Cerri and Cerri, 2007; Neil et al., 2005; Wick et al., 2005; Garcia-Montiel et al., 2001), and forests (Luizão et al., 1989; Melillo et al., 2001, Keller et al., 2005), but few studies have investigated emissions from croplands in the Amazon region. The variability in edaphic and climatic conditions in the Amazon basin is enormous, which makes research on this topic even more important. Within the region, there are many different scenarios of agricultural expansion occurring simultaneously, and these diverse situations will have different impacts on the way in which they alter natural processes and the rates at which these impacts occur. Within the region of western Pará State, for example, there has been a large front of expansion of mechanized agriculture during recent years, and few if any studies have been conducted in an attempt to evaluate the impacts caused by these activities and their effects on areas adjacent to these new centers of production. The area dedicated to soybean production in the region of Santarém, Pará State tripled between 1999 and 2002 (Lameira and Alencar, 2002), and was 28,150 ha in 2009, and was projected to reach 86,900 ha in 2010 (CONAB, 2012). The majority of this expansion has been in areas of secondary forest and pasture, with just 10% resulting from deforestation of primary forest (Venturieri et al., 2007). The area under soybean in the State of Pará, which was 86,900 ha in 2010 (CONAB, 2012), could triple by 2014 as a function of current market tendencies (FBOMS, 2004).

In light of this situation, this work had as its principal objectives the quantification of trace gas fluxes of N_2O, CO_2 and CH_4 in soils of the lower Amazon basin planted with soybean and rice, and the relation of this flux with soil chemical and physical parameters and also with precipitation. It was expected to find that N_2O emissions under soybean would be higher than those from soils under rice–because soybean is a legume with N-fixing ability and therefore increasing the nitrogen abundance in the soil. It was also expected that methane emissions would be higher in soils under rice cultivation, because of the lower oxygen content of these soils due to expected higher water content.

MATERIALS AND METHODS

This study was conducted in agricultural fields planted rice (*Oryza sativa*) and soybean (*Glycine max*), located near the cities of Belterra and Santarém in western Pará State, Brazil, during the production years of 2005 to 2007. The areas were initially planted with rice, then with soybean, both crops using a conventional management system, in the same area. During dry season this area was in fallow.

The region's climate is type Am in the Köppen classification

Table 1. Some physical and chemicals characteristics of clayey Yellow Latossols in Belterra municipality, Pará State (Two experimental sites).

HOR	Depth cm	Sand	ADA	Clay	C	Fe$_2$O$_3$	H$_2$O	ΔpH	Ca	Mg	K	S	Al	T	Silt/ clay	Ki	V	m	P
		(g/kg of soil)				pH			(cmol$_c$ kg^{-1} soil)						clay	%			(mg/kg)
Typic Hapludox – coordinates: 02º54'S e 54º56'W																			
A1	0 - 11	30	640	890	19.8	61	3.7	-0.1	0.40		0.05	0.50	2.70	10.5	0.09	1.91	5	84	4
AB	23	20	510	920	13.6	63	4.1	-0.3		0.30	0.03	0.45	2.10	7.8	0.07	1.86	5	84	2
BA	45	20	0	930	9.6	66	4.3	-0.4		0.40	0.02	0.44	1.80	5.9	0.05	1.86	7	82	1
Bw1	91	20	0	930	6.4	67	4.4	-0.4		0.30	0.01	0.32	1.70	4.4	0.05	1.88	7	85	1
Bw2	160	10	0	930	4.2	67	4.7	-0.6		0.40	0.01	0.44	1.00	3.6	0.06	1.92	11	71	1
Typic Hapludox – coordinates: 02º 45'S e 54º54'W																			
O	3 - 0	160	50	680	55.9	41	4.8	-0.8	6.8	3.2	0.23	10.3	0.3	22.9	0.24	2.03	13	89	1
A1	0 - 15	100	50	820	18.1	49	4.5	-0.5	0.5	0.5	0.04	1.1	1.6	8.4	0.10	1.99	5	92	<1
AB	29	70	68	840	11.3	52	4.5	-0.5	0.4		0.02	0.44	1.7	6.4	0.11	1.98	1	90	<1
BA	44	60	0	870	7.9	52	4.7	-0.6	0.50		0.02	0.53	1.5	4.6	0.08	1.94	1	88	<1
Bw1	79	70	0	870	5.1	52	4.9	-0.9	0.40		0.01	0.42	1.3	4.0	0.07	1.94	1	91	<1
Bw2	122	60	0	890	5.0	55	5.0	-1.0	0.40		0.01	0.42	1.3	3.5	0.06	1.92	1		
Bw3	200	50	0	880	4.0	54	5.0	-1.0	0.40		0.01	0.43	1.1	3.5	0.08	1.95	1		

ADA, Clay dispersed in water.

system (IBAMA, 2004), and the soils are predominately clayey Oxisols on slightly undulating terrain, classified by the Brazilian Soil Classification System (Embrapa, 1999) as Typic Hapludox, with an average clay content above 850 g kg^{-1} (Table 1) (Moraes et al., 1995; Rodrigues et al., 2001).

In the city of Santarém, annual average air temperature varies between 25.4 and 27.1°C, and relative humidity is high year-round with an average of 86.7%. Precipitation indices present large annual variation with an average of 1920 mm (INMET, 2010), and there are two distinct seasons: a rainy season from December to May, and a dry season from July through November. In the city of Belterra, annual average temperature varies between 25 and 28°C with an average annual relative humidity of 86%. Precipitation also occurs in two distinct periods, with a dry season from July to January presenting a monthly average of 62.5 mm, and a rainy season from February to June with an average of 770 mm (INMET, 2010).

Experimental design

Sampling was done in two 1 ha monoculture fields of soybean and of rice. In each of the 4 fields, 10 static chambers were randomly distributed for each sampling event. During the crop cycle (and concurrent with sampling), mineral fertilizer was applied to both crops at a rate of 400 kg ha^{-1} (2% N, 45% P, and 60% K), and nitrogen fertilizer was applied at a rate of 60 kg ha^{-1} of urea (60% N) 60 days after plant emergence. Soybean productivity was 3,180 kg ha^{-1} (± 400 kg) per year; rice productivity was 3,000 kg ha^{-1}.

Sampling was divided into 3 stages: Period 1: From initial seedling planting (day zero) to day 7, with daily sampling to verify the effects of fertilizer application; Period 2: Day 8 up to harvest day, with sampling conducted once a week; Period 3: Harvest day to day 5 after harvest, with sampling done each day.

Gas sample collection protocol

The static chamber method was used to sample N$_2$O and CH$_4$, following the protocol described in Keller et al. (2005). Chambers were randomly installed in the field and inserted into the soil to a maximum depth of 3 cm. For each sampling event, 10 chambers were sampled and at each chamber 4 samples were taken. Sampling began by placing a lid on top of the base 5 min after the chamber base was put in the soil. Samples were taken using a nylon syringe at 1, 10, 20, and 30 min after the lid was put in place. Air temperature at the height of the chamber and at 2 cm in the soil were measured a digital thermometer and the chamber height was measured at 3 internal points to calculate gas concentration.

Collected samples were transported to the gas chromatography laboratory at Embrapa Amazônia Oriental in Santarém and analyzed using a Shimadzu (GC 8A) gas chromatograph within 24 h. N$_2$O and CO$_2$ were determined using an electron capture detector (ECD), with injector,
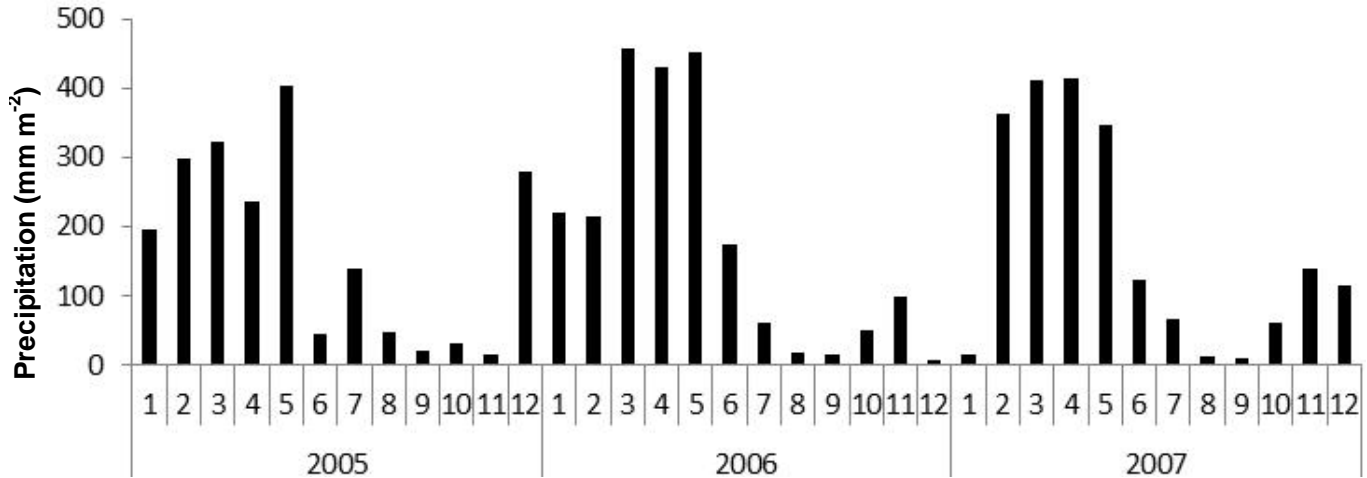
Figure 1. Total precipitation during entire study period.

detector, and column temperatures of 330, 330 and 80°C, respectively. Peaks of gas concentration were compared to primary standards (calibrated to National Institute of Standards and Technology) containing known concentrations of N_2O (308.1 and 753 ppb) and CO_2 (969 and 30000 ppm). Concentrations of CH_4 were determined using a flame ionization detector (FID), injector, detector, and column temperatures of 125, 125 and 40ºC, respectively. Peaks of CH_4 concentration were compared to primary standards (calibrated to National Institute of Standards and Technology) containing known concentrations of 1.75 and 0.884 ppm.

Gas fluxes emitted from the soil surface (F) were calculated from the linear correlation of gas concentration over the sampling time using Equation 1:

$$F = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \frac{m}{Vm} \qquad (1)$$

Where: ΔC = change in gas concentration within the chamber; (Δt) = time that the chamber remained closed; V and A are, the volume and the area of the soil covered by the chamber, respectively, and m = molecular mass of each gas (N_2O, CH_4 and CO_2)

Soil sampling

Soil was sampled at 10 cm depth from inside the area covered by the chamber immediately after gas collection was finished. Samples were placed in labeled plastic bags and transported to the laboratory for weighing on a precision balance to obtain wet mass. Soils were dried at 105ºC for 48 h in an oven and then weighed again to obtain dry mass.

Water filled pore space (WFPS; Linn and Doran, 1984) was calculated using soil bulk density (dg), soil particle density (dp) and the concentration of water in the soil (u), according to Equations 2 to 4.

(2)

(3)

(4)

Where: θ = soil moisture (%); α = soil pore space (%); dg =soil bulk density (g cm^{-3}); dp = soil particle density (g cm^{-3}), and u= concentration of water in the soil (%).

Statistical analysis

Data analysis was done using the program Statistica 8.0 (Statsoft Inc.). Normality was tested, and when necessary data were log transformed (CO_2= log (CO_2); N_2O = log (N_2O + 60), CH_4= log (CH_4 + 650), in mg m^{-2} h^{-1} (CO_2), µg m^{-2} h^{-1} (N_2O and CH_4), respectively. Differences were tested using one-way analysis of variance (ANOVA) and the Tukey post-hoc test. A probability level of α = 0.05 was used for all tests. Linear regression was used to investigate possible relationships between soil moisture content and gas flux.

RESULTS

Precipitation and soil moisture

Rainfall is highly seasonal in the research area and the monthly totals during the study period (January 2005 to December 2007) are shown in Figure 1. Most agricultural activities took place in the rainy season with 70% of annual precipitation occurring during this season.

In the rice fields, WFPS displayed an increasing trend throughout the study, with the second period often being the wettest. During the 2005 rice crop cycle, WFPS values averaged 39% and the highest value (43%) during the second period. Year 2006 was a wetter, with annual soil moisture above 58%, and with the highest value (69%) again during the second sampling period. Year 2007 was the wettest of the three years, with annual WFPS values above 55% and period 3 being the wettest this year (61%; Table 2).

In the soybean fields WFPS decreased over time with no period being consistently wetter. In 2005, WFPS was 61, 64 and 63% for periods 1-3, respectively, while in 2006, it was 47, 33 and 28% for periods 1-3, respectively.

Table 2. Average flux of N_2O, CO_2 and CH_4 and the standard error of the mean (±SEM) for the years 2005-2007 in mechanized soybean and rice fields. The periods (1, 2, and 3) represent cultivation phases.

Year	Treatment	N_2O ± SEM ($\mu g\text{-N m}^{-2} h^{-1}$)	CO_2 ± SEM ($mg\text{-C m}^{-2} h^{-1}$)	CH_4 ± SEM ($\mu g\text{-C m}^{-2} h^{-1}$)	WFPS (%)
Soybean					
	Period 1	1.9 ± 0.5	500± 57	-0.2 ± 0.3	60.6±0.9
2005	Period 2	1.6 ± 0.4	131 ± 15	-0.8 ± 0.4	64.0±1.0
	Period 3	2.6 ± 2.8	120 ± 34	-0.2 ± 0.7	62.8±1.3
	Period 1	7.4 ± 2.3	178 ± 22	-0.1 ± 0.4	47.1±1.9
2006	Period 2	7.9 ± 1.0	155 ± 24	-1.3 ± 0.7	32.8±1.8
	Period 3	6.2 ± 1.6	143 ± 24	-0.5 ± 0.1	28.3±5.6
	Period 1	3.6 ± 0.9	104 ± 13	0.5 ± 2.9	22.6±2.0
2007	Period 2	2.6 ± 0.7	407 ± 36	0.1 ± 2.5	31.1±1.3
	Period 3	21.5 ± 3.3	122 ± 18	0.6 ± 5.6	34.2±3.7
Rice					
	Period 1	77.8±18.8	350 ± 32	-1,0 ± 0.4	35.0±2.1
2005	Period 2	5.3 ± 2.0	607 ± 54	-0.8 ± 0.9	43.0±2.7
	Period 3	1.8 ± 0.8	205 ± 17	6.6 ± 4.7	41.8±5.3
	Period 1	8.2 ± 1.6	135 ± 12	-1.2 ± 1.4	46.4±2.1
2006	Period 2	6.7 ± 1.4	245 ± 44	0.4 ± 0.3	69.3±2.1
	Period 3	5.8 ± 2.1	181 ± 41	-1.9 ± 2.9	60.2±1.3
	Period 1	3.3 ± 1.1	180 ± 22	-8.6 ± 12.3	51.2±1.4
2007	Period 2	3.4 ± 0.8	350 ± 45.3	0.1 ±2.6	55.2±2.0
	Period 3	2.9 ± 0.6	427 ± 48.8	0.04 ± 2.0	61.6±1.1

In 2007, the WFPS values were lowest, with periods 1-3 showing 22.6, 31.1 and 34.2%, respectively (Table 2).

In the rice fields, N_2O had an average cycle flux of 28.3 $\mu g\ m^{-2}$ in 2005, with a steep decrease from period 1 (seedling planting to 7 days afterward) to the other periods (Table 2). In 2006, the cycle average decreased to 6.9 $\mu g\ m^{-2}$, followed by a slight decrease through the end of the cultivation cycle. In 2007, the average of the three periods was even lower (3.2 $\mu g\ m^{-2}$) remaining stable during the three periods.

In the soybean plantation, in 2005, N_2O had little variation during periods 1-3 (Table 2). In 2006, N_2O fluxes were 4 times greater. While in 2007, N_2O fluxes decreased in the first two periods followed by a large increase in period 3.

In the rice plantation, CH_4 had the largest variation of the trace gas fluxes during the 3 years of the study with a 3-year average of -0.006 $\mu g\ m^{-2}$, and the values increased from period 1 to 3 with period 3 (harvest) showing the largest value (6.6 $\mu g\ m^{-2}$). In 2006, the fluxes for periods 1-3 were -1.1, 0.4 and -1.9 $\mu g\ m^{-2}$, respectively. In period 1 of 2007 the values for CH_4 flux was highly negative (-8.62 $\mu g\ m^{-2}$), with periods 2 and 3 having a flux of 0.1 and 0.04 $\mu g\ m^{-2}$, respectively.

In the soybean plantation CH_4 flux displayed similar trends. Period 1 for years 2005 and 2006 had a flux of -0.17 and -0.09 $\mu g\ m^{-2}$, respectively; decreasing in period 2 to -0.85 and -1.33 $\mu g\ m^{-2}$, for years 2005 and 2006, respectively. During period 3, the flux was -0.21 $\mu g\ m^{-2}$ (2005) and -0.49 $\mu g\ m^{-2}$ (2006). In 2007, the fluxes were 0.47, 0.11 and 0.63 $\mu g\ m^{-2}$ for periods 1-3, respectively.

During the cultivation cycle of rice in 2005, CO_2 had an average annual flux of 387.1 $mg\ m^{-2}$, with periods 1-3 having fluxes of 349.8, 607.0 and 205.4 $mg\ m^{-2}$, respectively. Flux values for 2007 were lower with an annual average of 318.6 $mg\ m^{-2}$, while period 1 had a flux of 179.7 $mg\ m^{-2}$ and period 2 had 349.5 $mg\ m^{-2}$. In the soybean plantation CO_2 in 2005 had an annual average flux of 500.36 $mg\ m^{-2}$, diminishing to 130.87 and 119.52 $mg\ m^{-2}$ for periods 2 and 3, respectively. The same pattern between periods was evident in 2006, with a flux of 177.6, 155.3 and 142.7 $mg\ m^{-2}$, for periods 1-3, respectively. In 2007, period 2 had a very high flux of 406.7 $mg\ m^{-2}$, while period 1 had 103.7 and period 3 had 122.3 $mg\ m^{-2}$.

In the rice crop, there were no statistical differences between periods of cultivation, but significant differences were found between years of cultivation ($F=25, 8$; $p < 0.01$) for CO_2 flux (Table 3). N_2O on the contrary, showed significant differences between years and also between periods; with period 1 different than 2 and 3, and 2 equal to 3. There were no differences found for CH_4 flux

Table 3. Average trace gas (N_2O, CO_2 and CH_4) flux values and the respective WFPS values (%) with standard error of the mean (±SEM) for years 2005 to 2007 in an area of mechanized cultivation of soybean and rice.

Crop	Period (years)	CO_2 (mg-C m^{-2} d^{-1})	N_2O ($\mu g.m^{-2}$)	CH_4 ($\mu g.m^{-2}$)	WFPS (%)
Rice	2005	443.9±30.6[a]	38.0±9.2[a]	-0.006±0.7[a]	39.2±1.6[a]
	2006	197.5±23.2[b]	7.0±0.9[b]	-0.6±0.8[a]	60.3±1.4[b]
	2007	310.8±24.4[c]	3.2±0.5[b]	-3.0±4.3[a]	55.5±1.0[b]
Soybean	2005	305.1±32.2[a]	1.8±0.4[a]	-0.5±0.2[a]	62.3±0.6[a]
	2006	166.8±15.0[b]	7.5±1.3[a]	-0.6±0.3[a]	40.4±1.4[b]
	2007	254.1±22.5[ab]	6.6±11.5[a]	0.3±0.3[a]	29.0±1.2[c]

*Different letters in the same columns and crop represent statistically significant differences ($p < 0.05$).

between years or periods. There were significant differences for WFPS between years and periods (F=56,4; $p < 0.01$); with period 1 different than 2 and 3, and 2 equal to 3 (Table 3).

In the soybean crop, CO_2 showed significant differences for years (F=10, 4; $p < 0.01$) and between periods (F=3.7; $p < 0.05$), with period 1 equal to 2 and different than 3, and 2 equal to 3. N_2O had significant differences between years (F=12, 4; $p < 0.01$) and between periods (F=14.4; $p < 0.01$), with period 1 equal to 2 and different than 3, and 2 equal to 3. Trends for CH_4 and WFPS followed those for the rice crop.

DISCUSSION

The high frequency of sample collection during the period of crop management was important to be able to evaluate the effects of rice and soybean crop systems on the emission of N_2O. Furthermore, the soil preparation management in the soybean crop, together with high temperatures and rainfall, represent a unique situation to measure N_2O emission in the soil-atmosphere continuum.

With respect to N_2O flux, there was a significant difference in the soybean plantation in relation to period (F=10.4; $p < 0.01$) and also for year (F=21.8; $p < 0.01$), which could be explained by the greater availability of N in period 1 compared to the other periods. This greater availability of N is probably associated with good conditions for nitrifying and denitrifying bacterial activity (Firestone and Davidson, 1989). This is related to soil tilling under conventional management prior to seedling emergence that stimulates organic matter cycling, O_2, temperature, and moisture conditions (Dobbie and Smith, 2001) that favor N availability, which is reflected in greater N_2O emission (Table 3). These results are similar to those for young pastures in the Amazon rich in available N (Davidson et al., 2001). Greater availability of N and conditions of WFPS > 60% (Table 2) favor denitrifying bacterial activity in this system which should result in greater emission of N_2O (Oenema et al., 1997, Davidson et al., 2001). This is one of the causes of the positive

significant relationship between N_2O and WFPS in the soybean crop. Anaerobic conditions associated with high concentrations of N, principally in the form of nitrate (N-NO_3^-) represent ideal conditions for high denitrifying bacterial activity (Smith et al., 2003), which could also explain the elevated flux found in period 1 in soybean in all the years studied.

The data for emission of N_2O in this study are lower than those related in studies done in primary and secondary forests in the Amazon. Palm et al. (2002) reported an annual N_2O flux of 9.1 μg m^{-2} in secondary forest in Peru. Keller et al. (2005) found average annual N_2O fluxes of about 75 μg m^{-2} on a clay soil and 16 μg m^{-2} on a sandy soil in primary forest in the Brazilian Amazon.

Various studies have reported elevated N_2O emissions in soybean crops during 20 days before and after harvest (Yang and Cai, 2005; Ciampitti et al., 2005, 2007). These high levels of emissions are apparently related to greater concentrations of labile C as a product of node senescence, which is used as a primary substrate by the microbial population, favor the growth of all microbes but in particularly the nitrifying and denitrifying bacteria (Ciampitti et al., 2005). Escobar et al. (2010) found that N_2O emissions after soybean harvest were three times greater in no-till compared to a conventional management system. In the Peruvian Amazon, Palm et al. (2002) found that N_2O fluxes in high and low input annual agricultural systems were 2 to 3 times higher than those in secondary forest and 3 to 10 times higher compared to perennial tree-based systems. Greater N_2O emission could be related to a greater proportion of soil pores being filled with water in this clayey soil, a product of the property of having many small pores and high levels of moisture (Skiba and Ball, 2002), which would reduce O_2 diffusion, thus, through microbial competition for O_2, creating anaerobic sites (Baggs et al., 2006), favoring N_2O emission through denitrification. Therefore, we can conclude that, in 2005 and 2006, the maximum emission of N_2O in these conventional agricultural management systems occurred in period 1, decreasing in period 2, and then increasing in period 3 (Table 2).

High levels of WFPS lead to an increase in anaerobic microsites causing an exponential increase in N_2O emissions (Smith et al., 2003). In the present study, N_2O emissions from the soil under conventional agriculture increased with increasing WFPS, which is in agreement with other studies that reported a greater denitrification rate in soils with higher water content (Bateman and Baggs, 2005; Liu et al., 2006). Interestingly, in the Amazon, Wick et al. (2005), found no relationship between soil N_2O emissions and WFPS in pastures. In the current study, when WFPS exceeded 50% in this system, N_2O emissions dramatically increased. This is consistent with the results of Keller et al. (2005) in primary forest in the Brazilian Amazon. Palm et al. (2002) found large increases in N_2O flux with a doubling or tripling of WFPS in soybean, rice, and corn cropping systems in the Peruvian Amazon. In this case denitrification would be the dominant process (Moreira and Siqueira, 2006; Aita et al., 2007). The transition point between the processes that operate aerobically (nitrification) and anaerobically (denitrification) is frequently cited as 60% WFPS (Sehy et al., 2003; Webb et al., 2010). During the 2005 and 2007 crop cycles, after period 2 the soy crop had an increase in N_2O emission, probably due to the increase in available N in the soil caused by the fall of senescent leaves and the senescence of roots and rhizome nodules, as shown by Yang and Cai (2005) in soybeans.

During the 3 years of soy cultivation, soil respiration, which is determined by root and microbial activity (Cattani et al., 2002), could have been influenced by soil preparation and addition of N fertilizer which may have provoked the high CO_2 flux in period 1 compared to the 3 years of flux (Table 2). However, other factors such as WFPS and soil temperature have been discussed as being possible controllers of CO_2 flux from the soil to the atmosphere (Carvalho, 2005; Kuzyakov, 2006).

After seedling planting, the high availability of N could stimulate microbial activity leading to an increase in soil respiration. Furthermore, it is likely that soil preparation through tillage increased soil aeration and increasing the availability of labile organic matter that was previously protected by aggregates (Follett, 2001). High mineral N availability could have been responsible for the high CO_2 flux in period 1 during N fertilization activities, as compared to CO_2 flux for all years (Table 1). It is probable that fertilization had stimulated the absorption of N in the initial phase of soybean cultivation, and as a consequence, increased root and microbial respiratory activity. Carvalho (2005) demonstrated that N availability explained 66% of the flux of CO_2 in savannah soils cultivated with corn under different management systems.

In period 2, compared to all 3 years, there were high fluxes of CO_2, just as in period 1. This pattern could be due to the growth cycle of soybean, being accelerated just after N fertilizer application, thus stimulating the autotrophic component of the soil and increasing soil CO_2 flux (Table 2). The same pattern in flux is comparable to that obtained in an Oxisol in São Paulo State by La Scala et al. (2006). Additionally, the highest flux determined after soil preparation (Table 2) could be explained by the liberation of CO_2 previously produced through microbial action decomposing residual organic matter exposed by the physical fracturing of the soil or by root respiration (D'Andréa et al., 2006).

In 2007, CO_2 flux in period 1 was inferior compared to period 2, and although N fertilizer was applied in period 1; this difference could be in response to the limited addition of N associated with a smaller C: N of soluble material and also to the capacity of microbes to adapt to conditions of low availability of N (Marques et al., 2000). The high CO_2 flux values in period 2, when compared to the other periods could possibly be due to soil preparation during seedling planting. Various studies have attributed the increase in CO_2 flux during the initial phase of cultivation to the destruction of soil structure and the exposition of organic matter to microbial action (Reicosky and Lindstrom, 1993).

The two biggest peaks of CH_4 flux during the rice crop cycle could be related to the availability of C for methanogenesis from residues from the previous crop, from production of organic matter by the growing crop itself, from soil organic matter, and from root exudates. Additionally, morphogenic changes in rice plants that occur in the final growth phase wherein plants reach the maximum number of tillers and panicles in the reproductive phase (Lindau et al., 1991), phases in which these peaks occurred. These results for methane production are similar to those found by Palm et al. (2002) in the Peruvian Amazon (range = 5.2 - 33 µg m^{-2}.h^{-1}) who attributed the positive flux of methane to high-input agricultural practices in a rice/soybean/corn system. Furthermore, these authors showed an inverse relationship with WFPS wherein the high-input agriculture system continued to produce methane even at just 45% WFPS. Interestingly, in the study by Palm et al. (2002) all the other treatments (low-input agriculture, shifting cultivation, agroforestry, peach palm plantations, and forest fallow) had CH_4 consumption.

The pulse in the CH_4 flux in the rice crop in period 3 of 2005 (6.58 µg m^{-2}) is a significant result when compared to annual values reported for forests in the Amazon (-30 µg m^{-2}) (Palm et al., 2002); (-12.5 µg m^{-2}) (Keller et al., 2005), and this result could be due to the production of organic compounds from the anaerobic decomposition of organic matter such as leaves and dried panicules. This could also be due to catabolism of labile organic compounds by methanogenic microbes (Neue et al., 1996), as well as to the increase in the exudation of organic compounds by roots, a process that increases as the plant develops. These exudates serve as substrate for methanogenic bacteria metabolism, thus increasing the production of CH_4 (Aulakh et al., 2001). According to these authors, there is a positive correlation between the
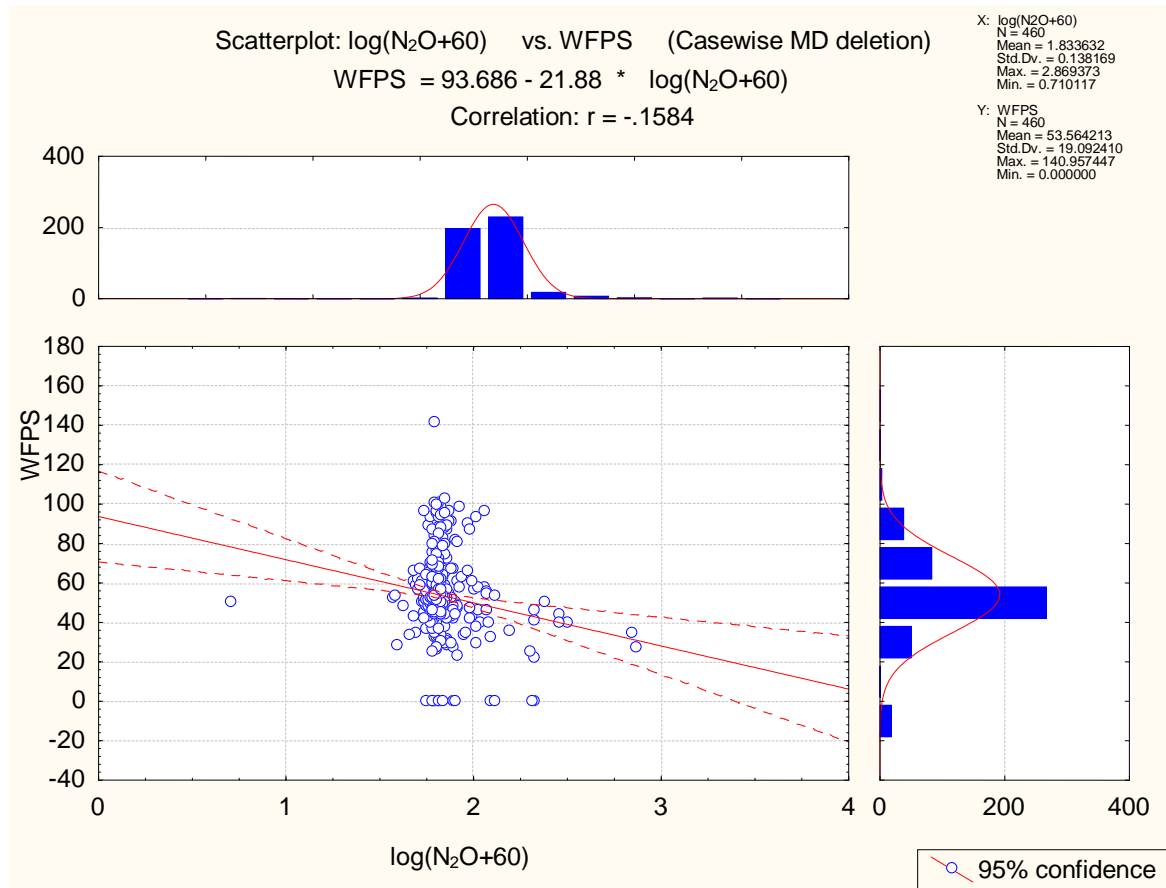
Scatterplot: log(N2O+60)   vs. WFPS   (Casewise MD deletion)

WFPS = 93.686 - 21.88 * log(N$_2$O+60)

Correlation: r = -.1584

X: log(N2O+60)
N = 460
Mean = 1.833632
Std.Dv. = 0.138169
Max. = 2.869373
Min. = 0.710117

Y: WFPS
N = 460
Mean = 53.564213
Std.Dv. = 19.092410
Max. = 140.957447
Min. = 0.000000

95% confidence

Figure 2. Correlation between WFPS x CO$_2$ (A), and WFPS x N$_2$O (B) in rice.

dry mass of roots and shoots in rice plants with the exudation of organic compounds by roots, so as the plant grows exudation increases, a process that is dependent on the photosynthetic rate of the plant, which in turn is dependent of available sunlight and the nutritional status of the plant (Taiz and Zeiger, 1991). However, in the initial phase of growth of rice cultivated in soil that has received residual plant matter, the largest contribution of C to methanogenesis is from the decomposition of these residuals and from the labile soil organic matter fractions, with less contribution from root exudates (Watanabe, 1999). In the present study, the conventional system of cultivation demonstrates the importance of the incorporation of crop residues and vegetation before the start of the next crop cycle, a practice that favors the accumulation of C, thus initially permitting greater fluxes of CH$_4$ and CO$_2$.

The increase of tillers and leaves, and consequently, the number of canals of escape of CH$_4$ from the soil through the plant, also could have contributed to the intensity of the first peak of CH$_4$ (0.44 µg m^{-2}) in period 2 of 2006 (Huang et al., 1997; Nouchi et al., 1990). This peak could also be related to the intense liberation of root exudates during the phases of panicule differentiation,

booting stage, panicule emission, and finally, florescence in the reproductive phase of rice (Aulakh et al., 2001). Furthermore, senescent leaves begin to fall at this stage forming a litter layer on the soil surface, and tillers that do not produce a panicule, senescent roots and their exfoliates, dead rice plants, and root exudates have a significant role in providing C to methanogenic organisms (Watanabe, 1999). Anaerobic decomposition of these materials reduced the redox potential and is a source of C for methanogenesis in inundated soils thus increasing the production of CH$_4$ (Lauren and Duxbury, 1993; Cai et al., 1997; Chidthaisong and Watanabe, 1997).

With respect to the flux of N$_2$O, the low values registered in rice soils in period 3 of 2005, and compared with the 3 periods of 2007, could be related to a low availability of N and to aerobic conditions since WFPS was <60% (Table 1). In general, Oxisols are characterized as being N-limited and present low nitrification rates (Nardoto and Bustamante, 2003), and only rarely the production of N-NO$_3^-$ exceeds the demand of microorganisms and roots.

Eichner (1990) found N$_2$O emission rates in agricultural soils cultivated with leguminous plants to be between 0.34 and 4.6 kg N$_2$O-N ha.year^1. In the present study,

Scatterplot: log(CO₂) vs. WFPS   (Casewise MD deletion)
WFPS = 68.912 - 6.858 * log(CO₂)
Correlation: r = -.1706

X: log(CO2)
N = 460
Mean = 2,238044
Std.Dv. = 0,475035
Max. = 3,377092
Min. = 0,672195

Y: WFPS
N = 460
Mean = 53,564213
Std.Dv. = 19,092410
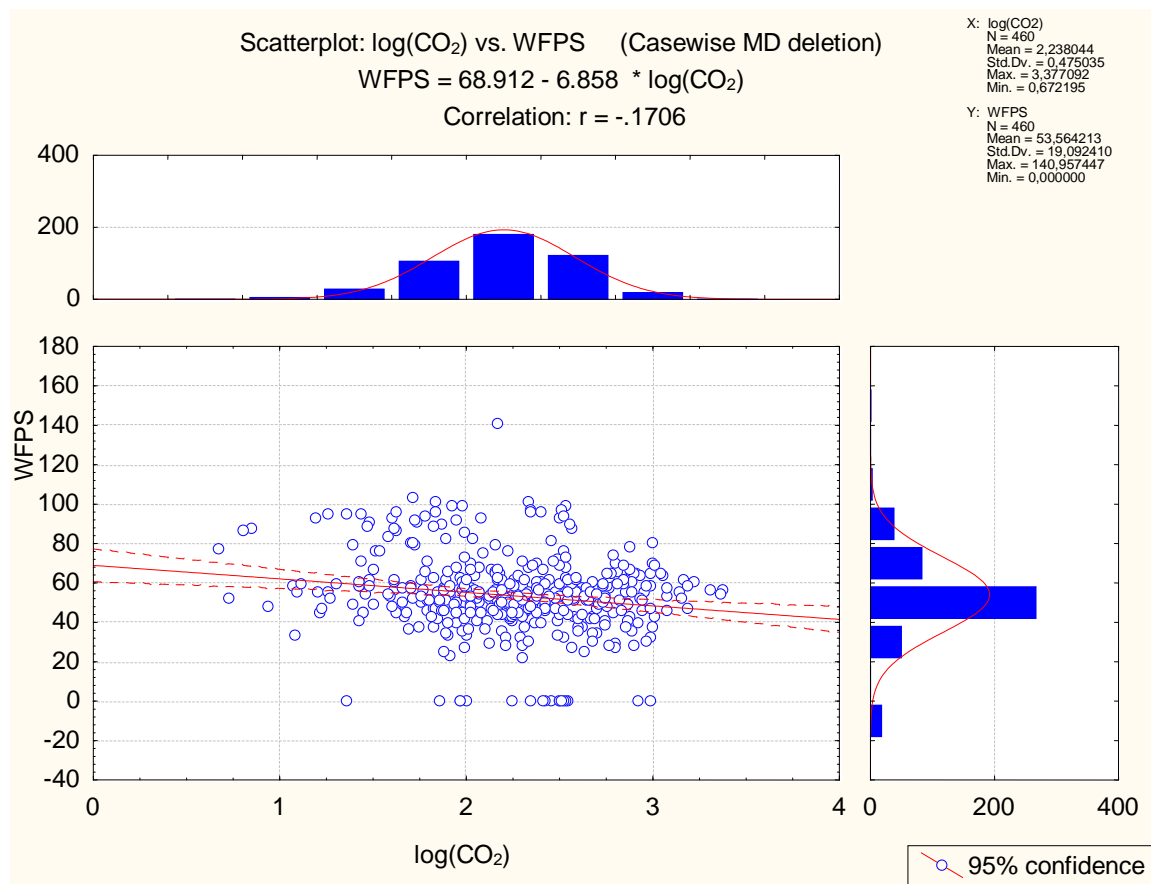Max. = 140,957447
Min. = 0,000000

95% confidence

Figure 3. Correlation between WFPS x N₂O in soybean.

fluxes varied between 0.53 kg ha year[1] and 0.90 kg N₂O-N ha year[1]; values that are lower than 2.3 and 1.27 kg N₂O-N ha year[1] in high- and low-input annual soybean/rice/corn agricultural systems in the Peruvian Amazon (Palm et al., 2002).

In Table 2, the rice crop had larger fluxes than the soybean crop in all study years, corroborating previous studies (Motschenbacher et al., 2014) that described the role of greater organic matter production by rice as compared to soybean and its relation to the gases analyzed in the present study. Furthermore, in the rice crop there was a significant correlation between the flux of CO₂ and N₂O with WFPS ($p<0.05$), as reported by other authors (Keller et al., 2005; Weitz et al., 2001), which can also be visualized in Figure 2.

In the soybean crop, this correlation was significant only for WFPS × N₂O (Figure 3).

Conclusions

There was annual variation in the rice and soybean crops for carbon dioxide and nitrous oxide, but there was no variation for methane between crops. There was positive

and significant correlation between N₂O nitrous oxide and WFPS in the soybean crop. During the period from initial seedling planting to day 7 (period 1), the rice crop emitted more nitrous oxide than in the period from day 8 up to harvest day or in the period from harvest day to 5 days after harvest the other two periods; in the soybean crop this happened more frequently in from harvest day to 5 days after harvest, (period 3). In general the gas fluxes (carbon dioxide, nitrous oxide, and methane) were greater in the rice than the soybean crop.

Conflict of Interest

The authors have not declared any conflict of interest.

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